MAGNETOPLASMADYNAMICS

NASA Langley Research Center
Langley Station, Hampton, Va.

Presented at Field Inspection of Advanced Research and Technology

Hampton, Virginia
May 18-22, 1964

MAGNETOPLASMADYNAMICS

Our discussion here will concern research in magnetoplasmadynamics. The three primary ingredients of magnetoplasmadynamics (which we shall call MPD here on) are plasmas, magnetic fields, and motion. Most simply, a plasma is an ionized gas which is a conductor of electricity. Anytime an electrically conducting plasma moves across a magnetic field, forces on the plasma are produced; this is the primary MPD effect.

In the last twenty years, there has been an almost explosive rise in research activity in MPD. This was due to two factors. One of these was the realization by astrophysicists that most of the universe is in the plasma state. The other factor was the attainment of high gas temperatures both in the flow about reentry vehicles and in the laboratory with such devices as electric arc heaters, shock tubes, and controlled-fusion research apparatus. The key effect of these higher gas temperatures was the production of plasmas having significant electrical conductivity. We can now say that the growth in laboratory research in MPD is tied most closely to the attainment of high-temperature plasmas and the desire to investigate phenomena of such widespread manifestations as MPD.

The first slide shows broadly the primary manifestations of MPD in nature and potential applications in space exploration and technology. First, astrophysicists now realize that more than 99 percent of the universe is in the plasma state, mostly in motion, and that there are magnetic fields in interstellar space, thus most cosmological phenomena involve MPD. In space exploration, we hope to generate power and provide propulsion by MPD means. In hypersonic flight, we expect to simulate reentry flows by accelerating plasmas and, with the advent of superconducting magnets, to provide MPD forces and heating control for reentry vehicles. Lastly, one of the largest research efforts, chiefly by the AEC, is directed toward "harnessing the H-bomb" or attaining controlled thermonuclear fusion to provide virtually unlimited power for worldwide needs.

In our presentation, we will limit our attention to one example of MPD research related to laboratory simulation of astrophysical phenomena, and to examples of plasma acceleration research which is related both to electric-propulsion and to reentry-flight simulation. We turn first to the area related to astrophysics.

LABORATORY ASTROPHYSICS

The experiment in this room will enable us to compress and heat matter in the ionized or plasma state to temperatures of many million degrees.

The next slide (LIGHTS OUT) illustrates the principle of the "magnetic-compression machine." On the right is a picture of the energy storage capacitor bank which you have just seen before entering this room. It can store one million Joules of electrical energy at twenty-thousand volts and can generate a peak current of twelve million amperes when discharged through the coil on the left. This corresponds to an average power level of about eighty billion watts, a value about equal to the average power generated in the United States. LIGHTS.

You can see the copper coil in front of you. The eight parallel sections are connected to two large collector plates which must be held together by more than 100 2-inch steel bolts and about 40 tons of lead. The magnetic field associated with the current is used for the compression and confinement of the plasma in the Pyrex tube inside the coil. In other words, magnetic pressure is exerted radially inward on the plasma.

Extremely high-temperature plasmas exist in the interiors of our sun and other stars and in the solar corona. Magnetic compression experiments can be used for the simulation and study of such plasmas.

The primary purpose of this particular experiment is the simulation of the solar corona. The next slide shows on the left a cross section of part of the solar atmosphere. The photosphere is often referred to as the surface of the sun; it is the solar disk as we normally see it and has a surface temperature of about 11,000° F. The chromosphere is a relatively thin boundary layer between the photosphere and the corona and is a very turbulent and complex structure. Magnetohydrodynamic shock waves traveling upward through the chromosphere are believed to be responsible for the high corona temperature of several million degrees. On the right you see a picture of the corona taken during a total eclipse, when the moon blacks out the photosphere. The gas in the corona accelerates to high speed and becomes the solar wind.

The next slide shows some of the types of radiation emitted by the corona as well as by our magnetically compressed plasma. The plasma in this experiment can produce as much radiation as 100 million cubic miles of the very tenuous coronal plasma, thus providing sufficient radiation for spectrographic study in the laboratory.

Detail studies of this laboratory-plasma provide basic data in atomic physics at very high temperatures where such data do not now exist; these results should form the basis for a quantitative theory of the corona. In turn, since the solar corona is in the form of the solar wind at the earth, with all its consequent effects on the earth's environment (such as the radiation belts, magnetic storms, etc.), a theory of the corona should accelerate understanding of these phenomena and will complement measurements made by astronauts, space probes, and space laboratories.

The complete experiment cannot be demonstrated to you because of the potential danger. However, we are able to show the preheating phase of the plasma which is necessary before magnetic compression can take place. The preheater capacitor banks on the mezzanines on your left and right can ionize the gas in the tube inside the coil and heat it to about 50,000° F. The flash you will see in the glass tube exists only for a short time and you must concentrate on our countdown in order to see it.

(DEMONSTRATION)

Bringing the atmosphere of the sun into a laboratory for direct observation sounds like an illusion; however, with the aid of magnetic compression, we are doing it here.

PLASMA ACCELERATOR RESEARCH

We turn now to basic MPD researches connected with plasma acceleration. Plasma acceleration demands research attention on several counts; for example, it appears now that plasma propulsion and plasma power generation are the candidates for interplanetary space missions beyond those to be covered by nuclear-rockets. Basic research related to these applications is in progress here and at our Ames and Lewis Research Centers; in addition, our Lewis Center, also carries out R and D work on actual electric-propulsion applications. You will see an exhibit in the hangar of their work. Nuclear-rocket study and development is under the NASA-AEC Space Nuclear Office at Germantown, Maryland. A second example of the use of plasma accelerators is as "wind tunnels" for laboratory study of hypersonic flight, including entry into planetary atmospheres. The attainment of such laboratory facilities has proven to be an extremely difficult problem, and, although shock tubes continue to provide needed data, facilities are still needed with longer test-flow times and much higher velocities. Plasma devices offer these possibilities.

We will discuss progress and results in two of our approaches to plasma acceleration, dealing first with the linear, crossed-field d-c plasma accelerator.

Linear, crossed-field d-c plasma accelerators.- The next slide shows an overall view of the 1-inch square, plasma accelerator apparatus, one of the accelerators of this type under study at Langley. The accelerating region itself cannot be seen and is shown in the next slide which is a schematic of the apparatus. Starting at the left, nitrogen gas is introduced into an arc which raises the nitrogen temperature to 10,000° F. Three-tenths of one percent of cesium in vapor form is introduced into the hot nitrogen where it is ionized, raising the plasma electrical-conductivity to the required value. The plasma is expanded in the nozzle to supersonic velocity before introduction into the accelerator channel. The channel in this test device is 1 inch square, 12 inches long, and contains 24 pairs of electrodes, indicated by the black segments, top and bottom. Power input is 400 kilowatts to the arc-plasma source and 350 kilowatts to the plasma in the accelerator. The magnetic field across the accelerator is applied by a large, water-cooled magnet. The accelerator "dumps" its flow into a low-pressure chamber.

Before proceeding to experimental results, note the pitot tube in the exit flow and the location of a camera at the top. The next slide shows two frames from a movie taken with this camera. The flow is up and is supersonic. Note the increase in velocity, due to EM acceleration, from 6500 feet per second to 20,000 feet per second. The density for the velocity of 20,000-feet-per-second condition corresponds to an altitude of 151,000 feet. These results can be seen more clearly in a short movie which will now be shown. (DESCRIBE MOVIE)

In research on accelerators such as this, a primary research problem under intensive study is the attachment of the discharges at the leading edges of the cathodes and the trailing edges of the anodes, leading to high current concentrations and consequent heating and erosion of the electrodes. A demonstration with a special research apparatus to study this problem will now be made.

(DEMONSTRATION) LIGHTS OUT

As the next research step on accelerators of the type just described, we are constructing a larger, higher-powered version to give much higher velocities. Design velocity in a channel 5 inches square is 40,000 feet per second. Two, 10-megawatt DC rectifier units are available for powering this large accelerator. One of these 10,000 kilowatt power units is seen in the large photo on your right.

Such accelerators still have major materials problems because of heating, if operated for extended periods. For this reason, we consider the primary application of this device to be simulation of entry into planetary atmospheres, for which application, running times of the order of seconds are acceptable. One of the primary aims in our research is to eliminate the seeding so that the final flow is un-ionized and uncontaminated as would be the case for undisturbed free air. We have had some success in these aims, including successful operation of three small accelerators without seeding. Operation of the 5-inch-square 40,000-foot-per-second accelerator without seeding will constitute the first major realization of laboratory simulation of reentry using plasma acceleration.

Hall-current plasma accelerator.- We turn now to a class of devices called Hall-current plasma accelerators. A Hall-current arises when a magnetic-field crosses an electric field, for which case, the ions and electrons, because of their different weight drift with different velocities, thus establishing a Hall current. In the rectangular accelerators just discussed, such currents generally lead to undesirable effects that are minimized by segmenting the electrodes, however, in the accelerators we describe now, circular Hall currents are established in coaxial geometries and put to work as the driving current.

The next slide shows one type of Hall current plasma accelerator distinguished by a longitudinal or axial electric field. The sketch shows axially-displaced electrodes to which is applied an electric field. A radial magnetic field, as shown, can be provided by a suitable arrangement of coils and an iron core in the central insulated tube. Gas is fed in at the left end and density conditions and electric and magnetic field values are set such that the ion motion is nearly linear from anode to cathode, while electrons are trapped in drifting circular motion about the axis. These electrons in circular motion represent a Hall current j_θ, as indicated. Such accelerators have produced velocities in the range of several tens of thousands of feet per second, however, their velocity is limited by diffusion and turbulence losses which appear at the higher magnetic field strengths that are necessary for high acceleration. Plasma oscillations and turbulence are the object of intensive research here at

Langley and at other laboratories. Plasma turbulence occurs in many plasma devices (including controlled thermonuclear-fusion research apparatus) and the search to minimize or avoid it has broad basic significance. In our tests of devices like this, we are making progress toward understanding these very complex turbulence phenomena and are experimenting with means to suppress them.

Coaxial plasma accelerators using constricted-arc and Hall-current acceleration.- We now go to another coaxial plasma accelerator which here combines Hall-current principles with magnetic nozzle and constricted-arc effects. The next slide shows such an accelerator. One phenomenon illustrated here is the constriction of the arc - discharge on the axis near the cathode tip. In this region of the discharge, the combination of self- and externally-imposed magnetic fields can accelerate the plasma by large magnetic-field gradients. This is the so-called "magnetic-nozzle effect." As the discharge mushrooms out toward the anode, the crossed electric and magnetic-field geometry gives rise to added Hall-current acceleration. The magnet coil and iron ring tailor the magnetic field so that the plasma rotates to establish the Hall current which combines with the large radial-magnetic-field component to provide large accelerating forces. We would like now to show you a movie of such a device in operation.

MOVIE

The movie shows the plasma jet impinging on a disk-thrust balance and in the same picture, a meter in the left-lower-corner indicating magnetic-field strength and a meter at the right indicating thrust. As expected, you will observe that the thrust increases as the magnetic field increases.

This last type of accelerator has been recently the object of intensive study here, at other NASA Centers and at several industrial laboratories. Velocities at one industrial laboratory up to 320,000 feet per second have been measured using the light gas, hydrogen. The device is thus of direct interest as a thrustor, but still has research problems. We have achieved velocities of 60,000 feet per second with a heavier gas, argon, and one industrial laboratory has attained 58,000 feet per second using nitrogen. Thus, the device also shows promise as a reentry simulator but needs the right gas and the ionization must somehow be quenched. Velocities of interest for reentry simulation range from 26 to about 70,000 feet per second for manned vehicles, perhaps up to top meteoritic velocities of 650,000 feet per second for unmanned objects and up to velocities of twice this value for solar-wind simulation. It is in sight for plasma accelerators to do this, but much basic research still remains to be done.

PRIMARY APPLICATIONS OF SCIENCE OF MAGNETOPLASMADYNAMICS

ASTROPHYSICAL PHENOMENA

COSMOLOGICAL, STELLAR, GEOPHYSICAL AND LABORATORY SIMULATION

SPACE EXPLORATION

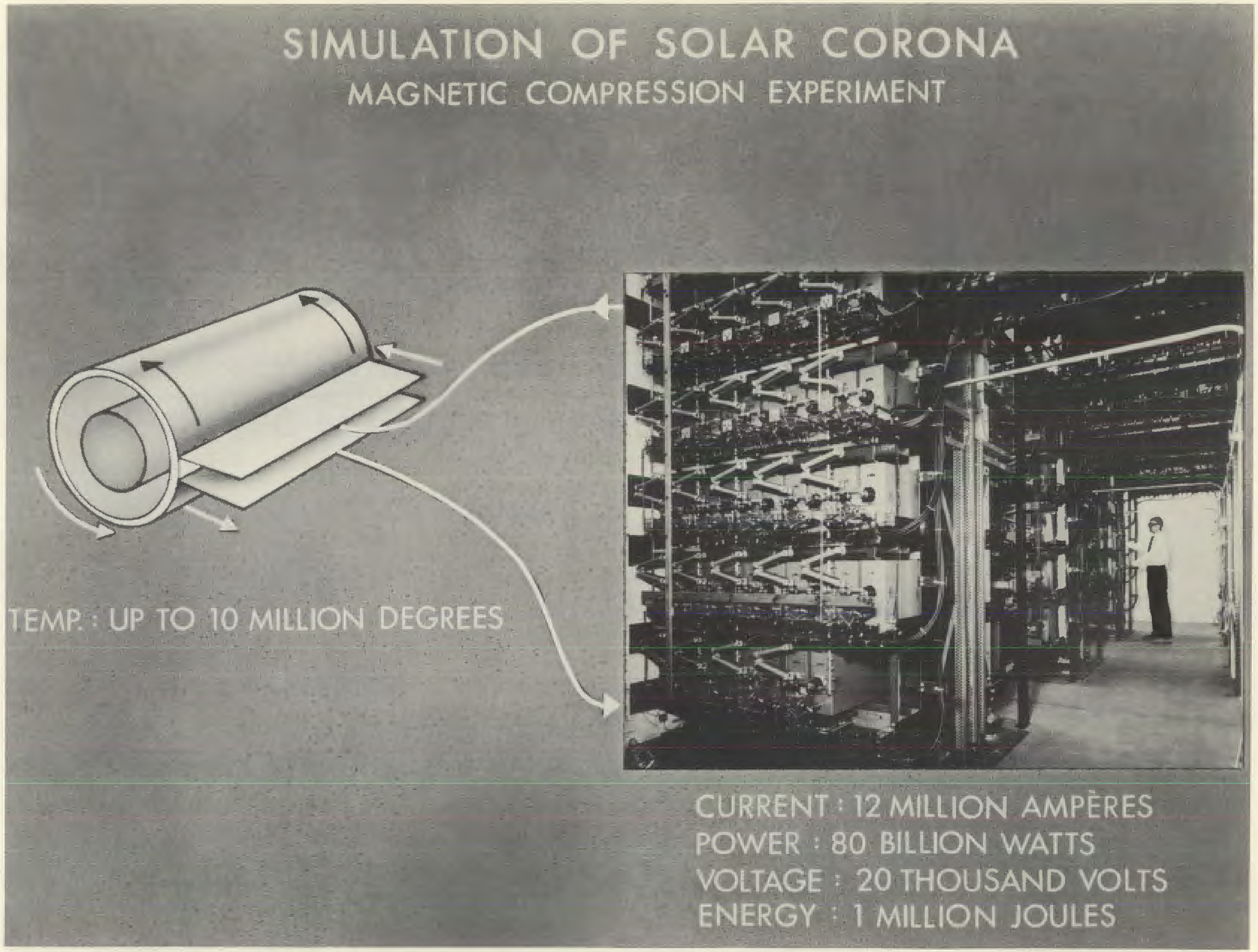
VEHICULAR POWER AND PROPULSION, ETC.

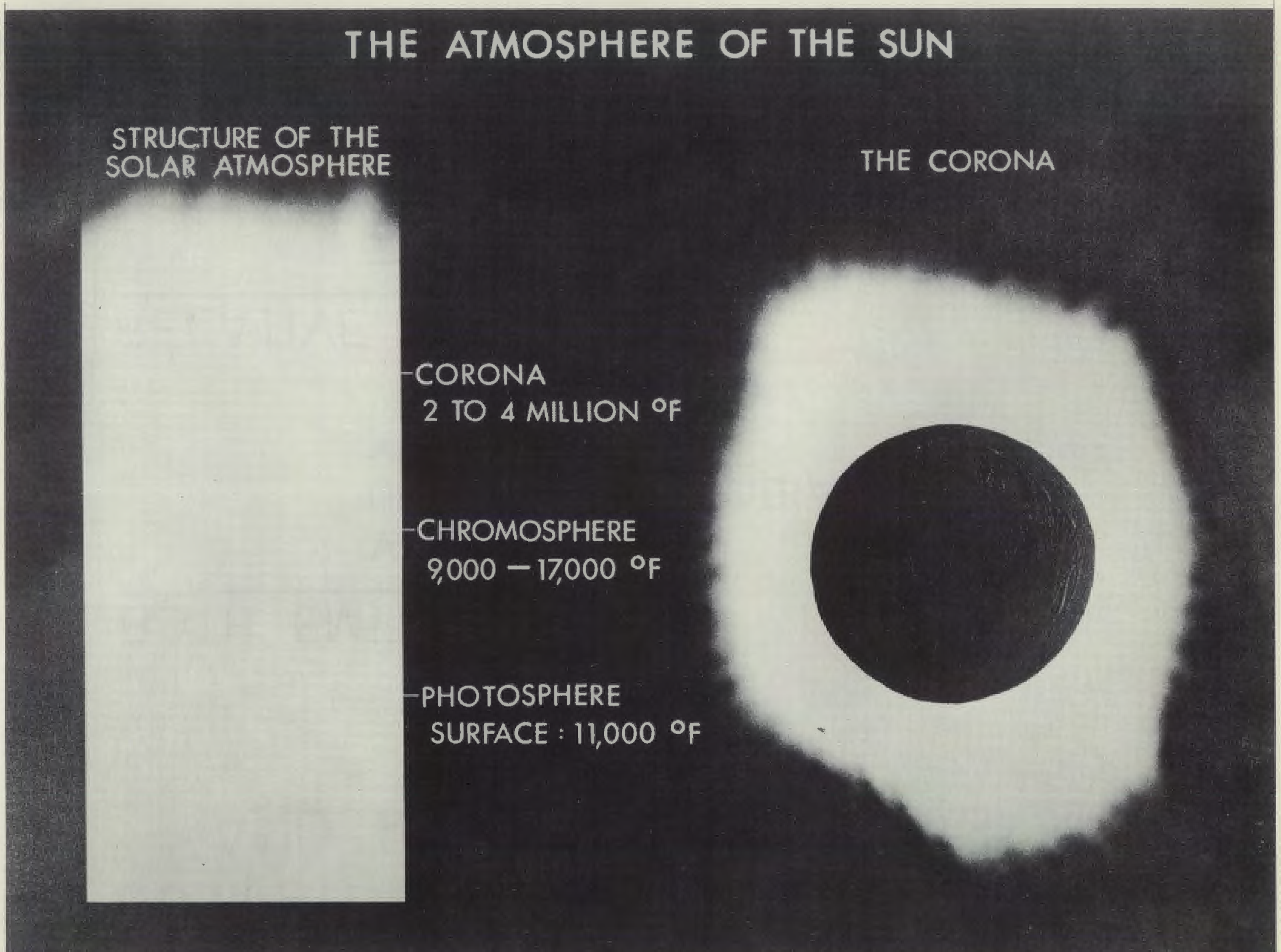
HYPERSONIC FLIGHT AND REENTRY

REENTRY FLOW SIMULATION, MPD FORCES ON VEHICLES

CONTROLLED THERMONUCLEAR FUSION

PLASMA PRODUCTION, HEATING AND CONTAINMENT


SIMULATION OF SOLAR CORONA
MAGNETIC COMPRESSION EXPERIMENT
TEMP.: UP TO 10 MILLION DEGREES
CURRENT: 12 MILLION AMPÈRES
POWER: 80 BILLION WATTS
VOLTAGE: 20 THOUSAND VOLTS
ENERGY: 1 MILLION JOULES


THE ATMOSPHERE OF THE SUN
STRUCTURE OF THE SOLAR ATMOSPHERE
THE CORONA
CORONA
2 TO 4 MILLION °F
CHROMOSPHERE
9,000 — 17,000 °F
PHOTOSPHERE
SURFACE : 11,000 °F

COMPARISON OF SOLAR CORONA AND LABORATORY PLASMA

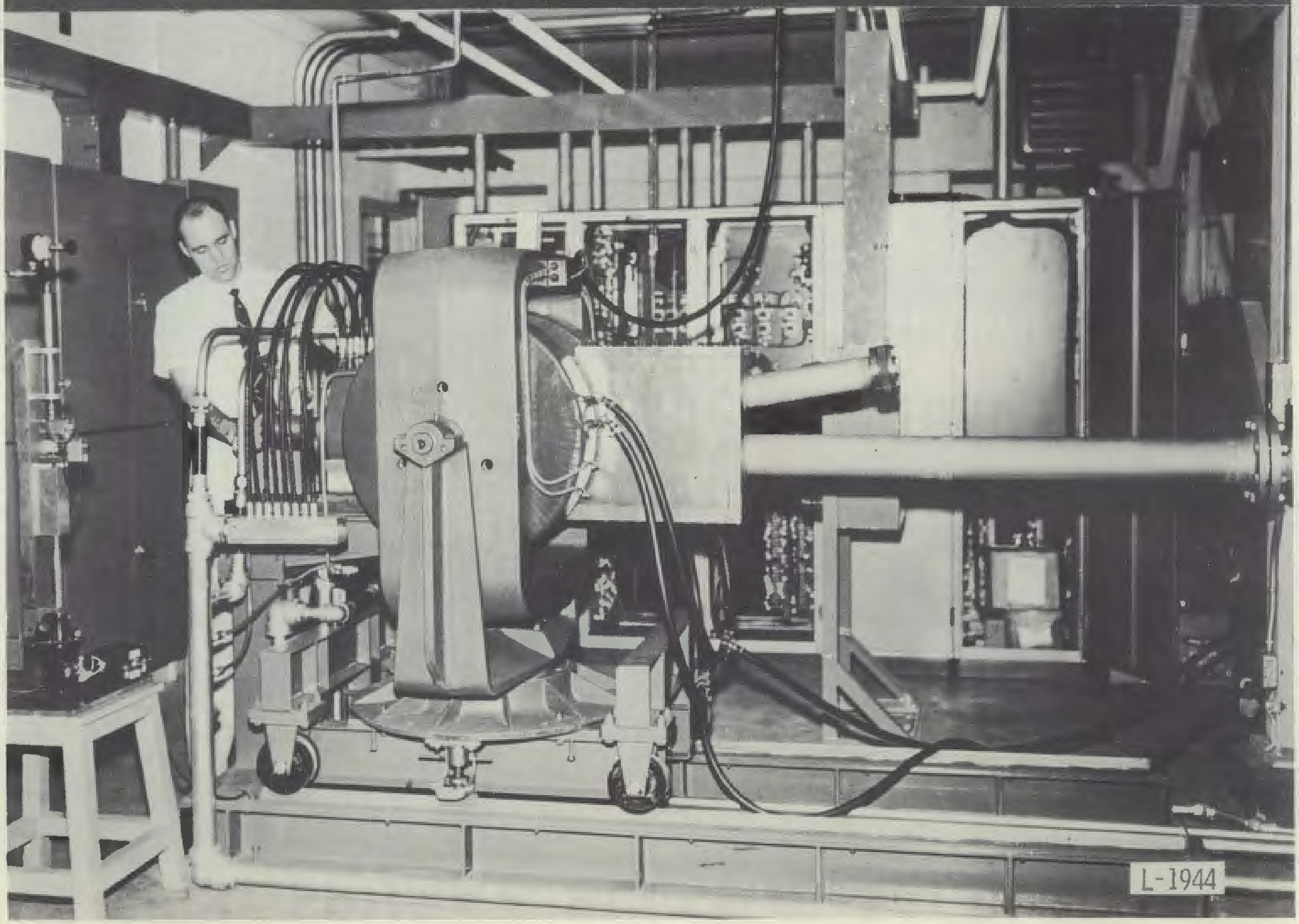
BOTH EMIT

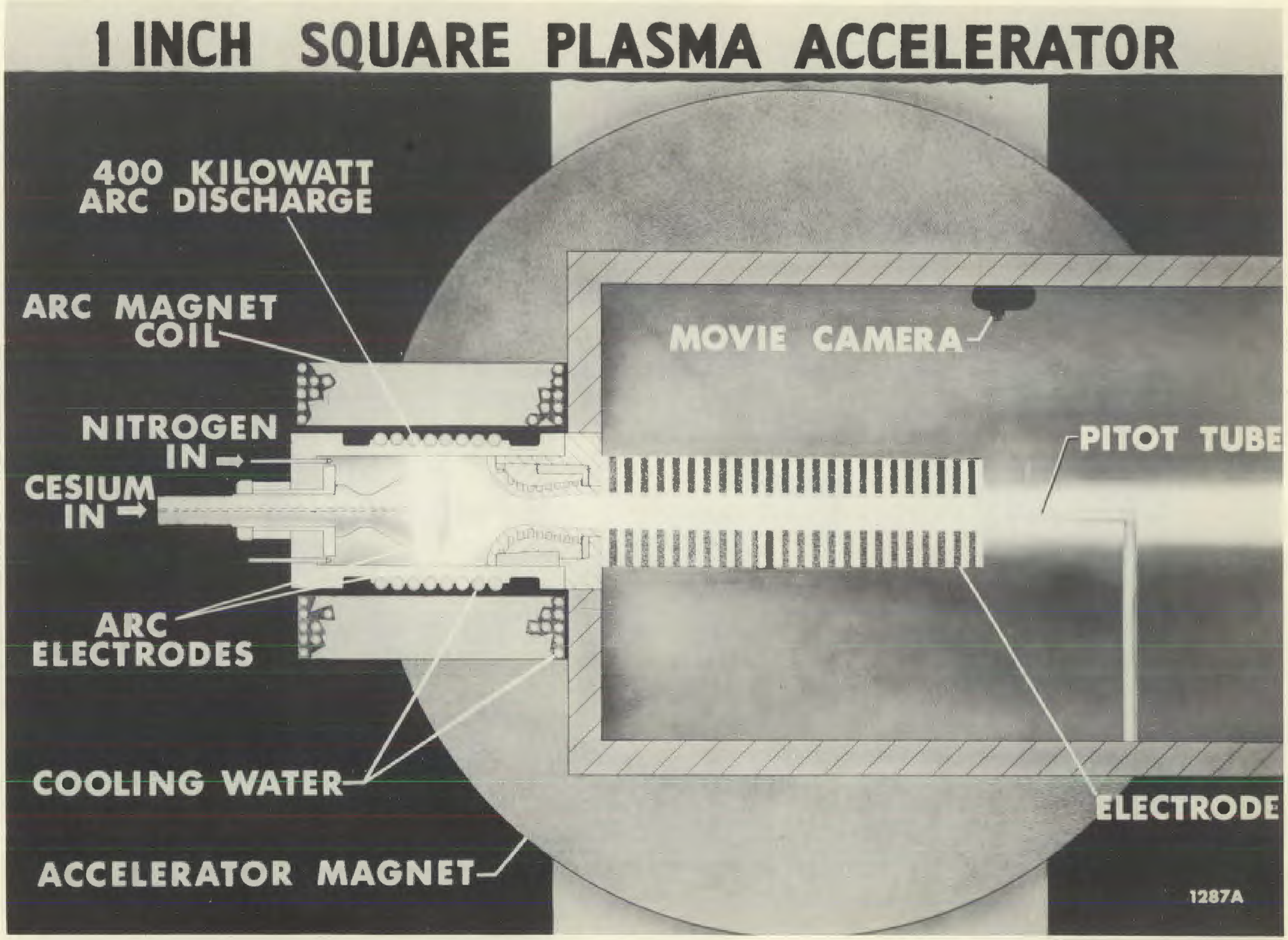
VISIBLE LIGHT
ULTRAVIOLET RADIATION
X-RAYS

RELATIVE INTENSITIES

THE PLASMA IN THIS EXPERIMENT CAN PRODUCE AS MUCH RADIATION AS 100 MILLION CUBIC MILES OF CORONAL PLASMA

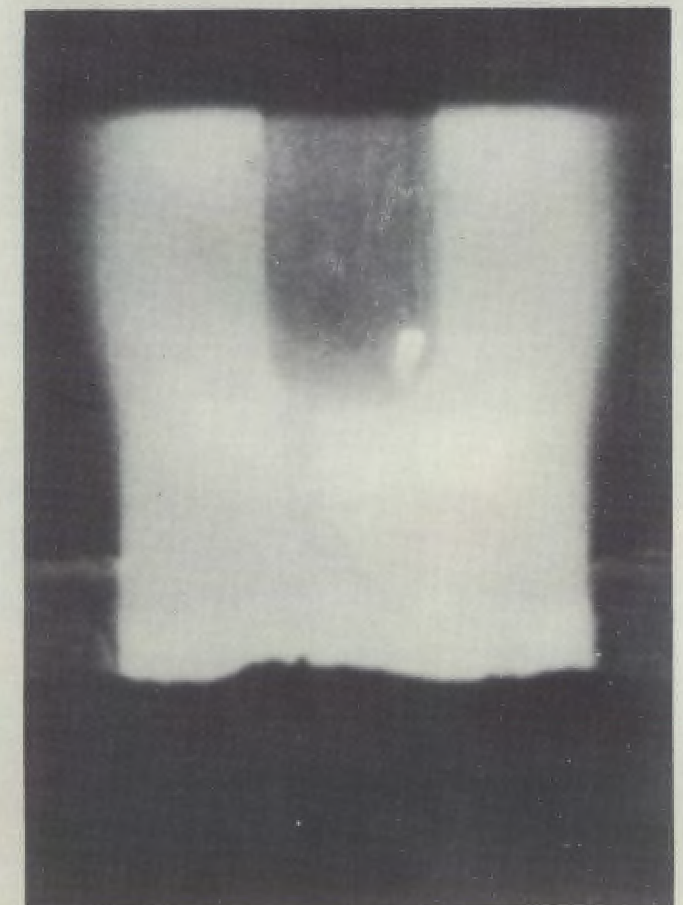
1-INCH SQUARE ACCELERATOR INSTALLATION



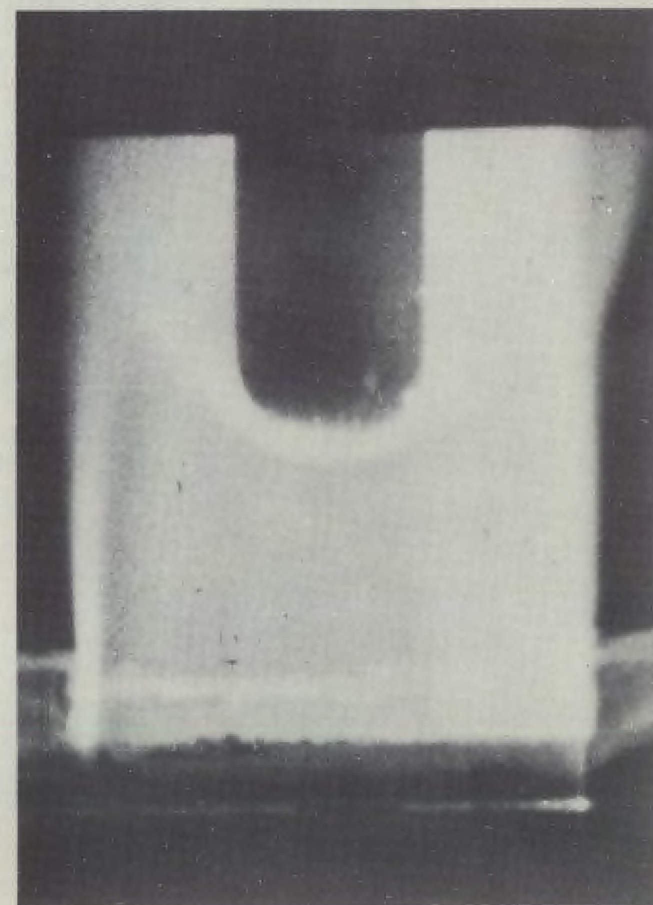

1 INCH SQUARE PLASMA ACCELERATOR
400 KILOWATT ARC DISCHARGE
ARC MAGNET COIL
NITROGEN IN
CESIUM IN
ARC ELECTRODES
COOLING WATER
ACCELERATOR MAGNET
MOVIE CAMERA
PITOT TUBE
ELECTRODE
1287A

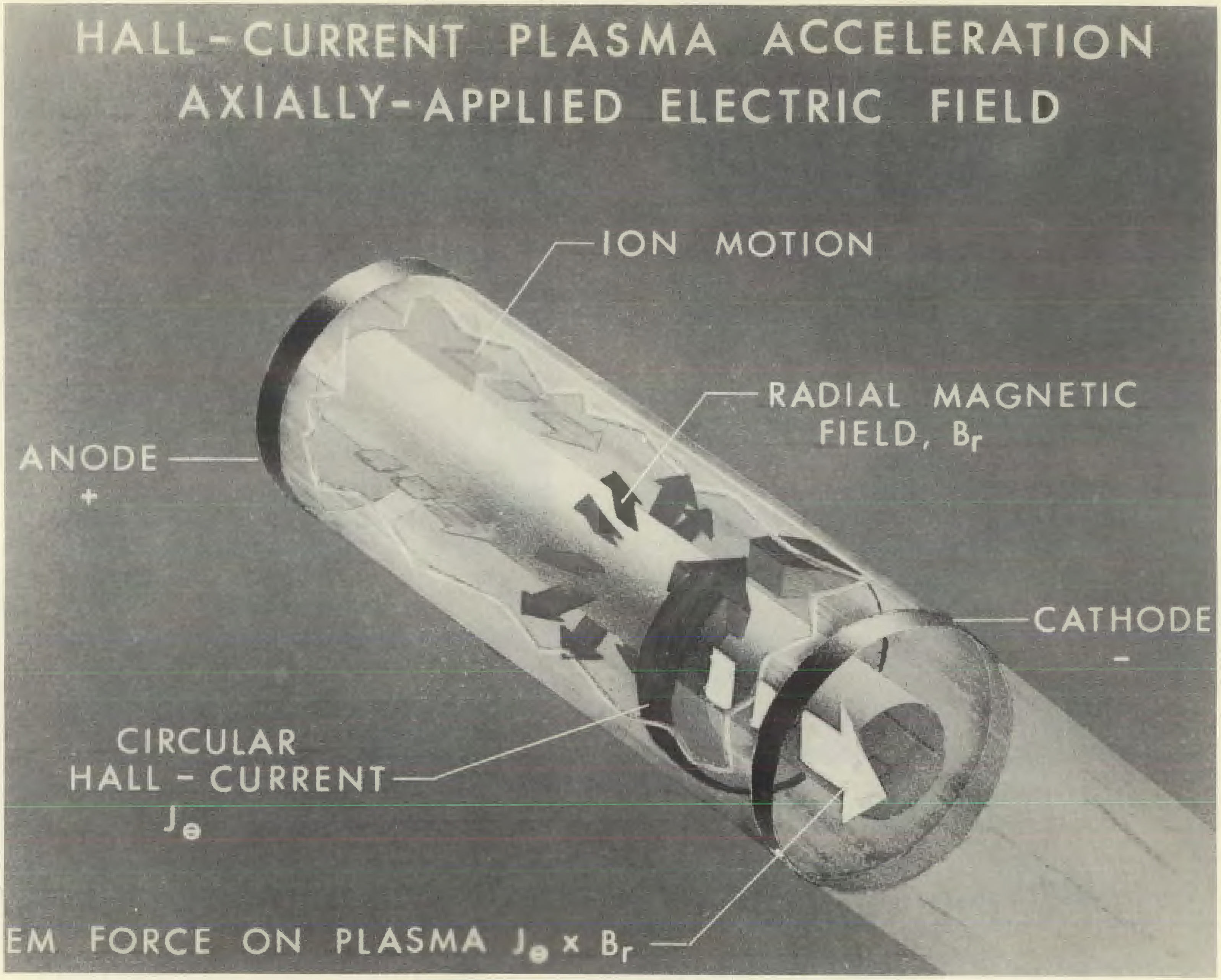
VELOCITY INCREASE DUE TO ELECTROMAGNETIC FORCE

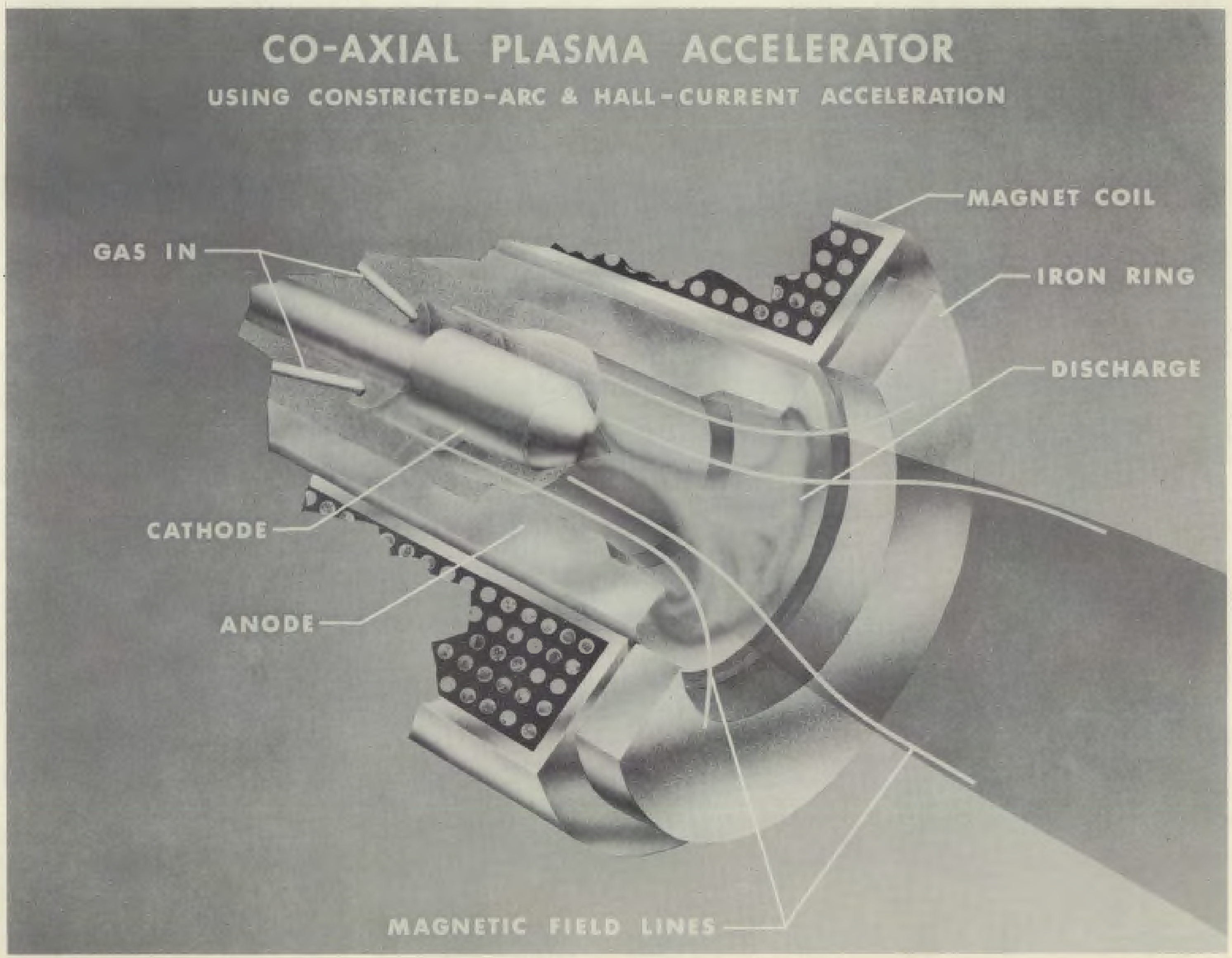
OFF: 6,500 FPS



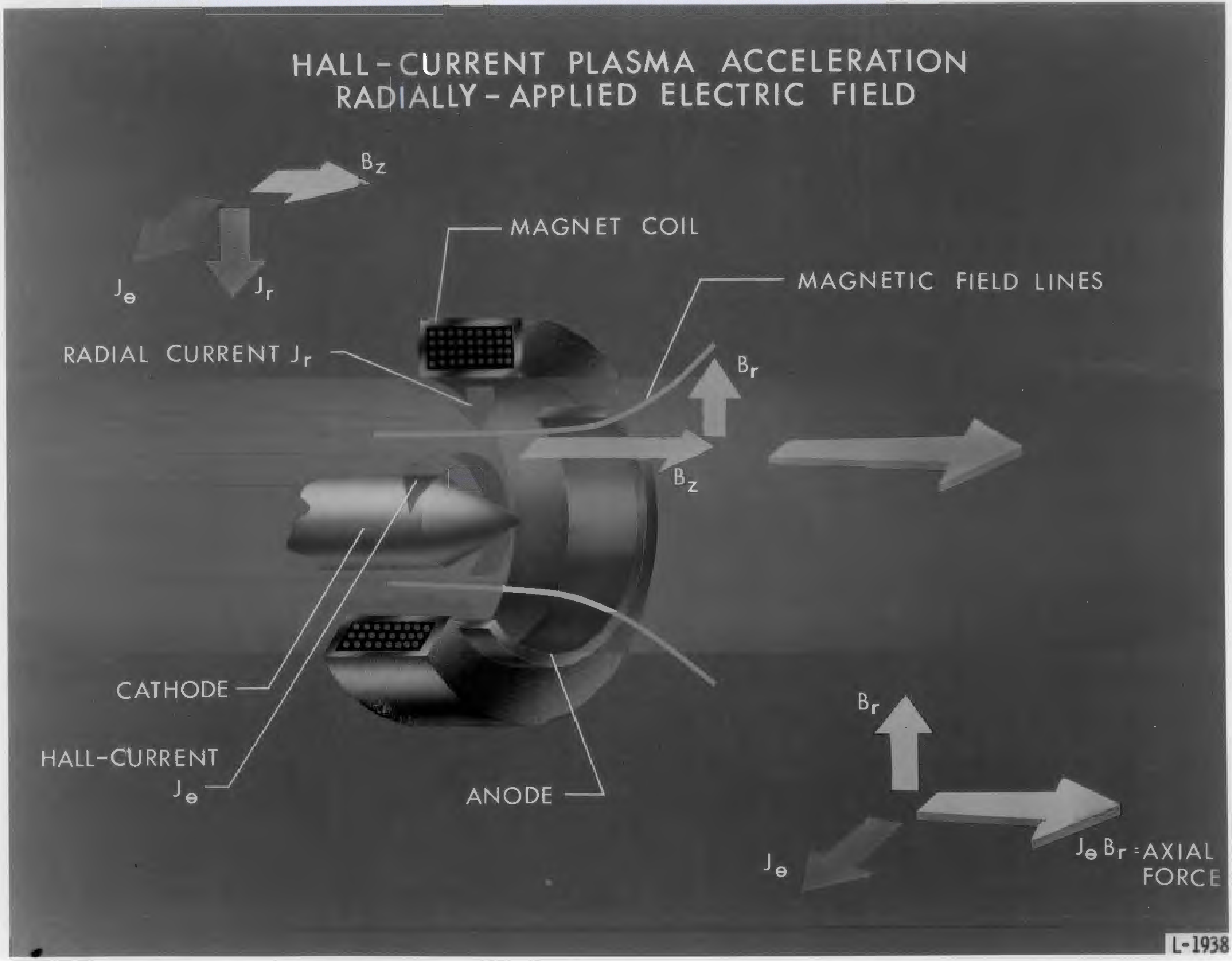
ON: 20,000 FPS




HALL-CURRENT PLASMA ACCELERATION
AXIALLY-APPLIED ELECTRIC FIELD
ION MOTION
RADIAL MAGNETIC FIELD, B_r
ANODE +
CATHODE -
CIRCULAR HALL-CURRENT J_θ
EM FORCE ON PLASMA $J_\theta \times B_r$



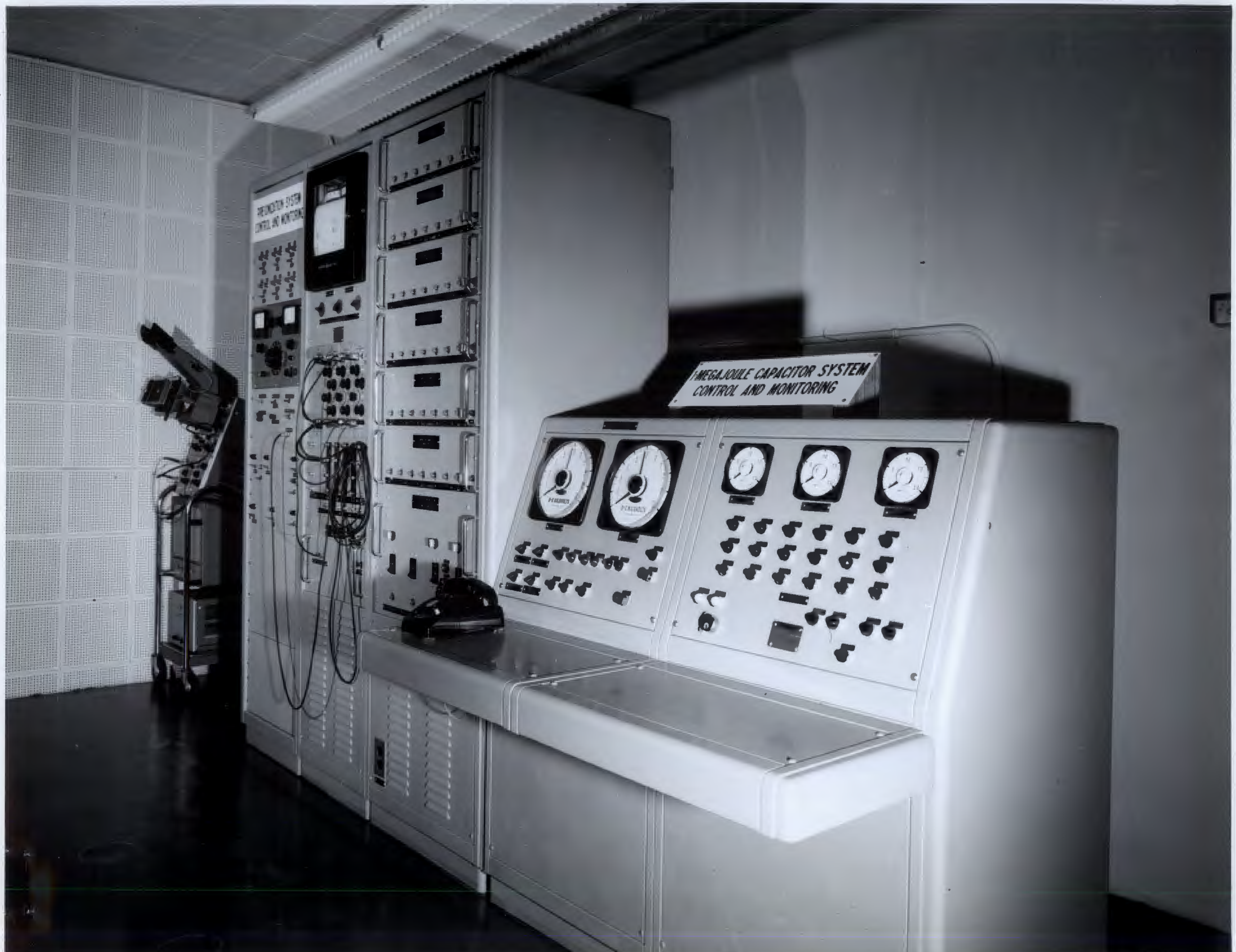
NASA-Langley, 1964


HALL-CURRENT PLASMA ACCELERATION
RADIALLY-APPLIED ELECTRIC FIELD
B_z
J_θ
J_r
MAGNET COIL
MAGNETIC FIELD LINES
RADIAL CURRENT J_r
B_r
B_z
CATHODE
HALL-CURRENT
J_θ
ANODE
B_r
J_θ
$J_\theta B_r$ = AXIAL FORCE
L-1938

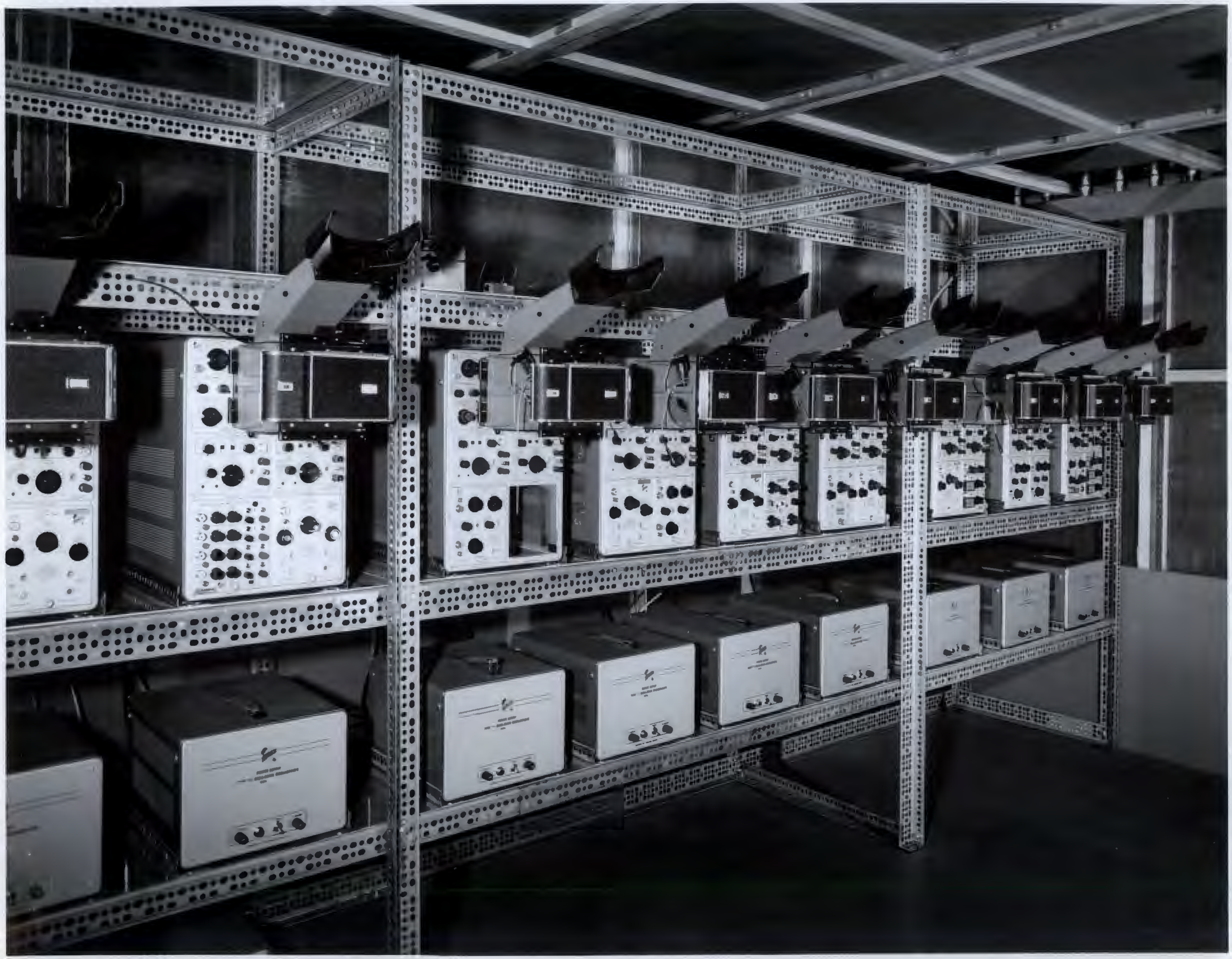
NASA
L-64-4866

NASA
L-64-4867

NASA
L-64-4868



NASA
L-64-4869



NASA
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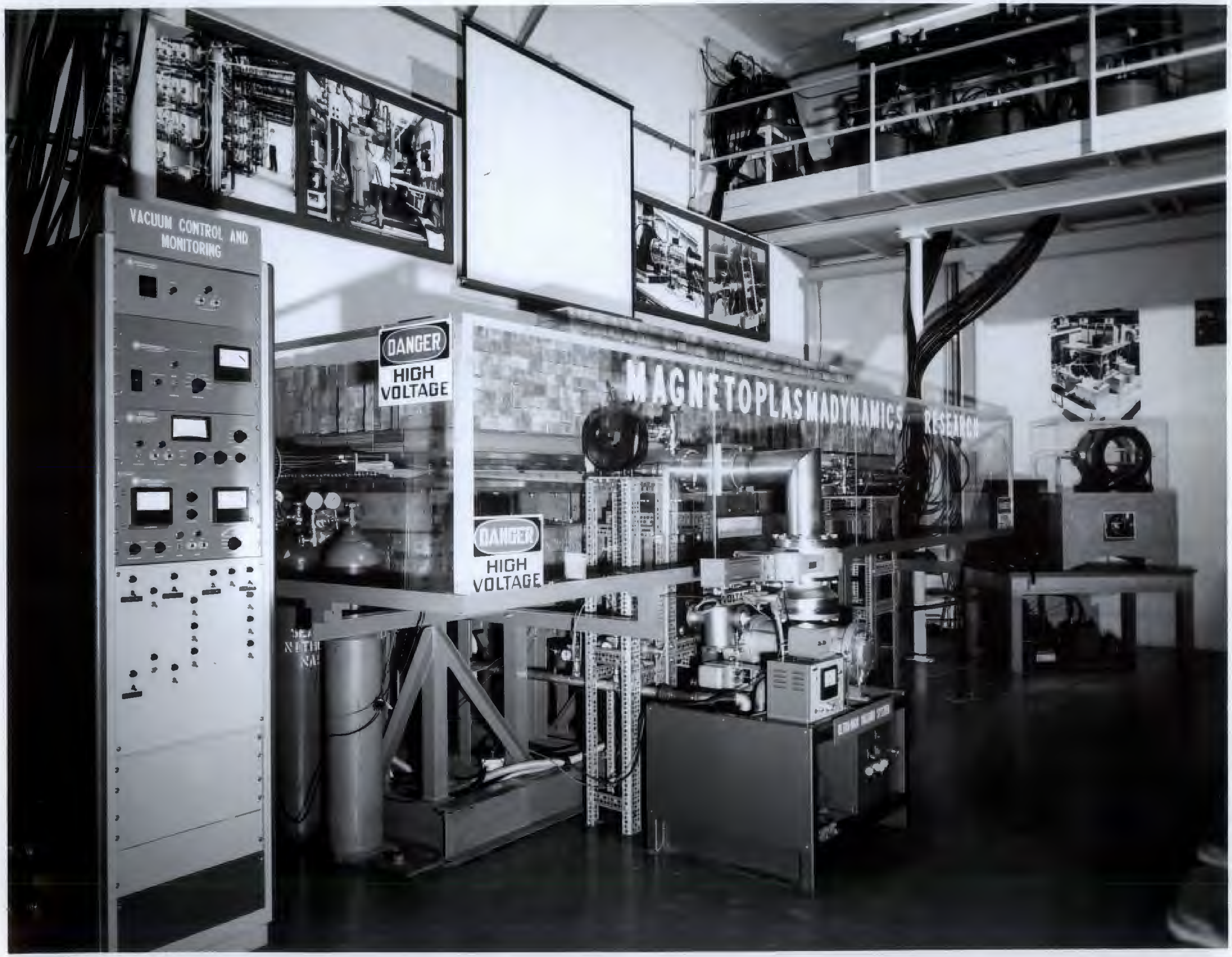

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